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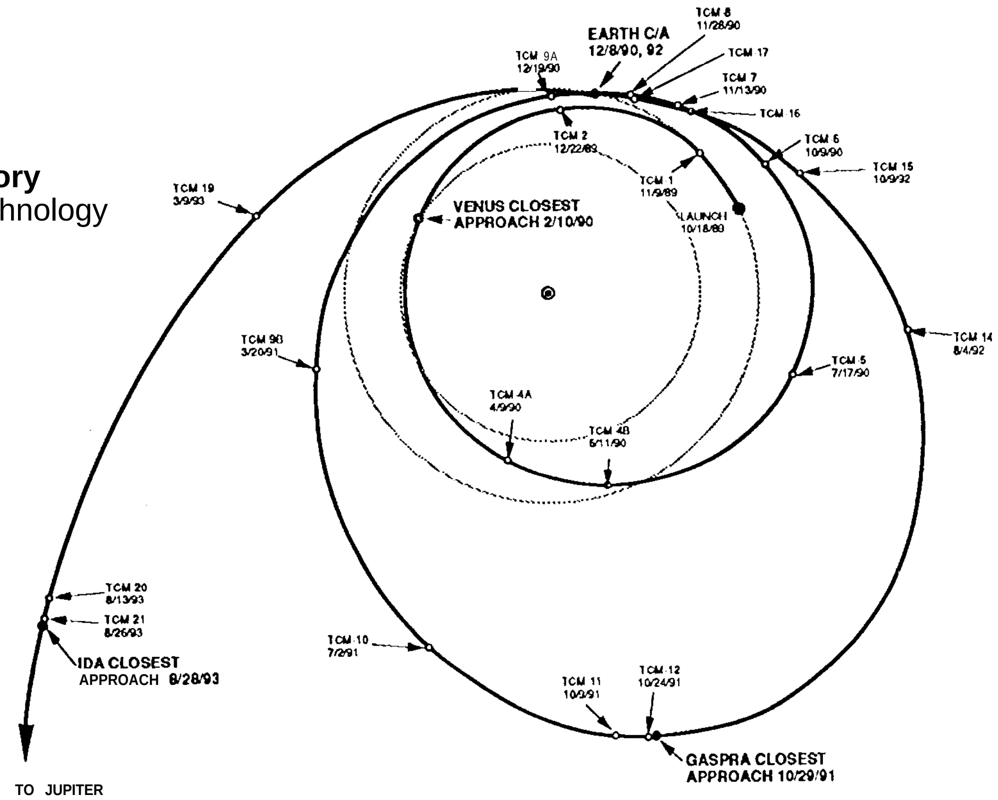

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After nearly four years of space flight, the Galileo spacecraft is finally on a direct trajectory to its final destination, Jupiter. It has taken three planetary gravity assists to achieve the energy necessary for Galileo to reach Jupiter. This Venus-Earth-Earth gravity assist route is referred to as the VEEGA trajectory. Each gravity assist required precise spacecraft delivery to the proper aimpoint to propel Galileo on the desired path to the next encounter. The maneuver design challenge has been to achieve the necessary flyby conditions in a propellant-optimal manner while accommodating both trajectory and spacecraft operating constraints. Unique maneuver design methods and tools have been utilized to meet this challenge and navigate the VEEGA trajectory successfully. The trajectory correction maneuver design process is evaluated by the degree to which the constraints arc satisfied, the delivery accuracy at each of the encounters, and through a comparison of pre-launch predictions with actual propellant consumption. Fu ture mission plans are also discussed, which include an encounter with the asteroid Ida on August 28, 1993, Jupiter atmospheric probe targeting, Jupiter orbit insertion, and finally an unprecedented two year tour of the Galilean satellites.

INTRODUCTION

The Galileo VEEGA (Venus-Earth-Earth Gravity Assist) trajectory, ill ust rated on the cover, besides providing a means for delivering Galileo to Jupiter, provided superb science opportunities enroute. As the name implies, the trajectory allowed for science observations of Venus and the Earth-Moon system. The two flybys of the Earth-Moon system accommodated science measurements of both the far side and north polar regions of the Moon. The Galileo VEEGA trajectory also included the first achieved and a planned second asteroid encounter

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(951 Gaspra and 243 Ida, respectively). This has all been a prelude to the main objectives, which are at Jupiter. An atmospheric entry probe will obtain the first in situ measurements of the Jupiter atmosphere, while the Galileo orbiter will investigate Jupiter, the Jovian satellites, and the Jovian magnetosphere. For a complete mission description see Reference [1].

The Galileo VEEGA trajectory is quite complex and challenging to the maneuver design process. The trajectory is controlled through twenty-four trajectory correction maneuvers (TCMs) scheduled within the first four years of the mission. By comparison, the Voyager II spacecraft took twelve years to perform a similar number of maneuvers. This paper identifies the goals, constraints, and results of the trajectory correction maneuvers designed for the Galileo VEEGA trajectory. Also discussed is the current status of propellant consumption, propellant predictions and the accuracy of predictions thus far, Actual TCMS arc compared with pre-launch predictions, and di screpancies are examined.

HISTORY

'there are two marked historical events which have had a significant influence on the Galileo maneuver design process. The first of these was the Challenger accident on January 28, 1986. In the Challenger aftermath, NASA canceled the Centaur upper stage for use in the Space Shuttle as a resul t of safety concerns having to do with the Centaur's cryogenic liquid propellant. The selection of the lower-energy Inertial Upper Stage (IUS) to replace the Centaur eliminated the possibility of launching Galileo on a direct transfer to Jupiter. The Galileo project considered many new launch vehicle and trajectory options, seeking a way to obtain the heliocentric energy increase necessary to reach Jupiter, while maintaining the desired science objectives at Jupiter. [2] Trajectory analysts on the Galileo project recognized that the same software used to design Galileo's complex gravity-assist tour of the Jovian system could be used to examine the interplanetary problem. It was soon discovered that one way to obtain the energy necessary to reach Jupiter with limited launch capability was actually to reduce the spacecraft's heliocentric energy. This energy reduction would be necessary to fly by Venus for the first of three gravity assists providing the required energy to reach Jupiter. It was in this manner that the low launch energy VEEGA trajectory was identified in August 1986 and soon adopted as the new mission baseline.[3]

The second incident which increased the Galileo maneuver design complexity occurred in 1988. A thruster on board the French TVSAT satellite overheated during operation and rendered itself and a nearby thruster useless. Because of design similarities, the Galileo 10 Newton thrusters were retested by the manufacturer and found to experience comparable difficulties under certain operating conditions. To avoid a similar misfortune, the decision was made in February 1989 to operate the Galileo 10 Newton thrusters only in a pulsed mode with low duty cycles and a confined operating range. The consequence of this decision was that large interplanetary TCMS could no longer be executed in a single day, but required execution over a longer period of time lasting up to a week, Pulsed mode thruster operation also had the effect of extending the time required to increase the spin rate of the spacecraft in preparation for using the larger 400 Newton engine. This delay resulted in increased propellant consumption predictions at Jupiter Orbit Insertion (JOI). The new 10 Newton thruster operating constraints created significant additional maneuver design and operation challenges less than a year before launch.

SPACECRAFT CONFIGURATION

Originally designed to accommodate 1 AU as the thermal environment extremity, the Galileo spacecraft needed modifications to prepare for its new route to Jupiter. Figure 1 shows the large sun shield added to shade the spacecraft bus and the smaller tip shade installed to protect the stowed high-gain antenna (HGA). Other shades were also required to safeguard the science instruments, the magnetometer and radioisotope thermoelectric generator (RTG) booms, and the probe relay antenna, In order for the sun shades to be effective, the spacecraft had to maintain the furled high-gain antenna and low-gain antenna nearly sun pointed inside a heliocentric distance of 1 AU. This resulted in extended periods of time early in the mission in which both antennas were pointed away from the Earth, To provide communication during these periods, an aft-pointed second low-gain antenna was affixed to one of the RTG booms.

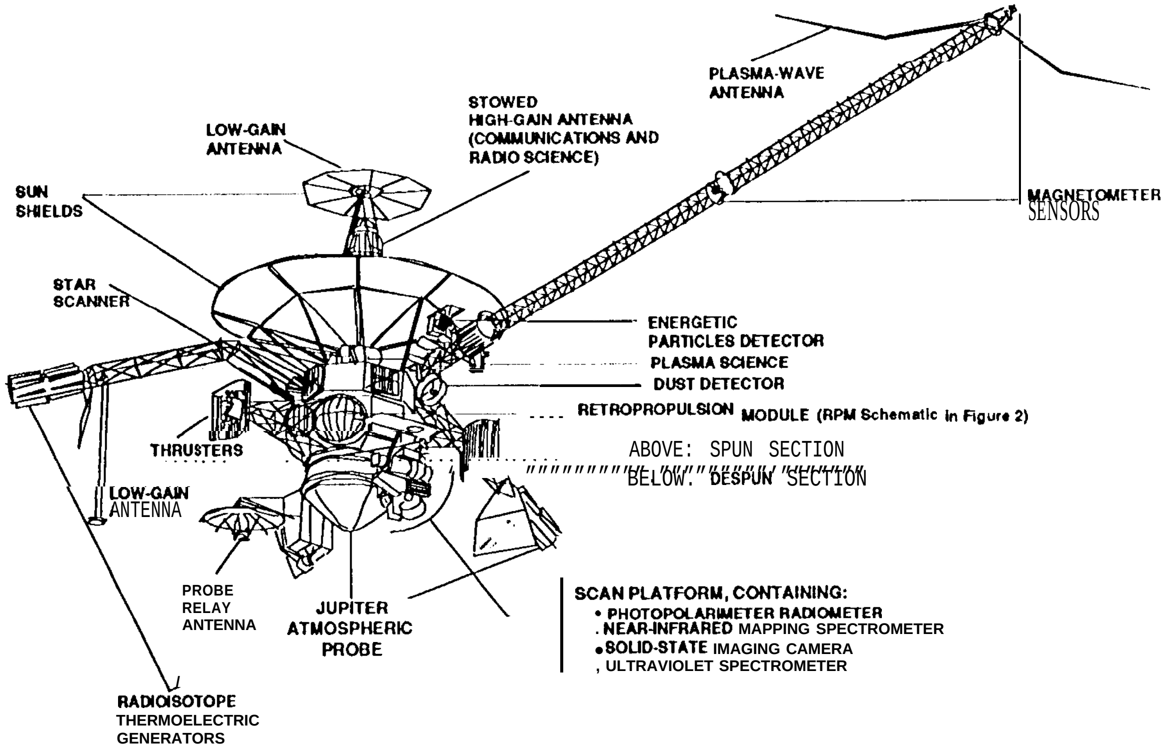


Figure 1: Galileo Spacecraft

The Galileo spacecraft is spin stabilized using a unique dual-spin design to accommodate both fields and particles and the remote sensing science instruments. There are six fields and particles science instruments mounted on the spun section of the spacecraft. The spacecraft rotation enables these instruments to sample the complete space around the spacecraft. Four of the five remote sensing instruments require stable pointing and are mounted with a common bore-sight on the scan platform. To accommodate these imaging science instruments, the despun section of the spacecraft was required to rotate at the same spacecraft spin rate of 3.15 revolutions per minute, but in the opposite direction. This section is, in effect, rotating with respect to the spinning spacecraft section, but with respect to an inertial frame it is fixed; hence the term despun. Six more science instruments are contained within the Jupiter atmospheric probe on the despun section of the spacecraft.

All velocity changes required in the Galileo mission arc implemented by the retropropulsion module (RPM) housed within the spun section of the spacecraft. The propulsion system was provided by the Federal Republic of Germany and built under contract by Messerschmitt-Bölkow-Blohm (MBB).[4] It is a bi-propellant, helium-pressure-fcd system with monomethyl hydrazine as the fuel and nitrogen tetroxide as the oxidizer. At launch, the usable propellant comprised 925 kg of the initial spacecraft mass of 2561 kg. The RPM includes t welve 10 Newton thrusters and one large 400 Newton main engine. The 10 Newton thrusters arc separated into two clusters of six thrusters each, and are used for trajectory correction maneuvers and control of both the spacecraft pointing and spin rate. The 400 Newton engine is planned to be used three times in the mission to provide large velocity changes. The 400 Newton main engine cannot be used until the probe is released (150 days before Jupiter arrival), since the probe covers the nozzle during transit to Jupiter.

Figure 2 is a schematic drawing of the RPM configuration with respect to the spacecraft coordinate directions. Two sets of redundant S-thrusters (-S1 A, -S1 B, and S2A, S2B) are used to maintain the nominal spin rate (3.15 rpm) and also to spin up (10 rpm) and spin down for probe release and main engine burns. There arc four -Z thrusters (-Z1 A, -Z2A, -Z1 B and -Z2B) of approximately 10 Newtons thrust each and the 400 Newton main engine oriented parallel to the spacecraft spin axis. These thrusters impart veloci t y changes, or AV, in the spacecraf t's -Z direction (high-gain antenna direction). Two L-thrusters (1.1 B and L2B) are canted 10° from the lateral direction and implement AV anywhere within the plane perpendicular to the spin axis through proper timing of the thruster firings as the spacecraft rotates. It is apparent from Figure 2 that there arc no thrusters positioned to implement a AV in the spacecraft's +Z direction effect ivel y. Of the two P-thrusters (PI A and P2A) canted 21" from the lateral direction, the 1'1 A thruster provides the largest available AV component (sin 210, in the +Z direction. This thruster's cant angle was limited to avoid plume impingement with the HGA. The spinning thruster configuration allows for a wide variety of methods for implementing a particular TCM AV vector.

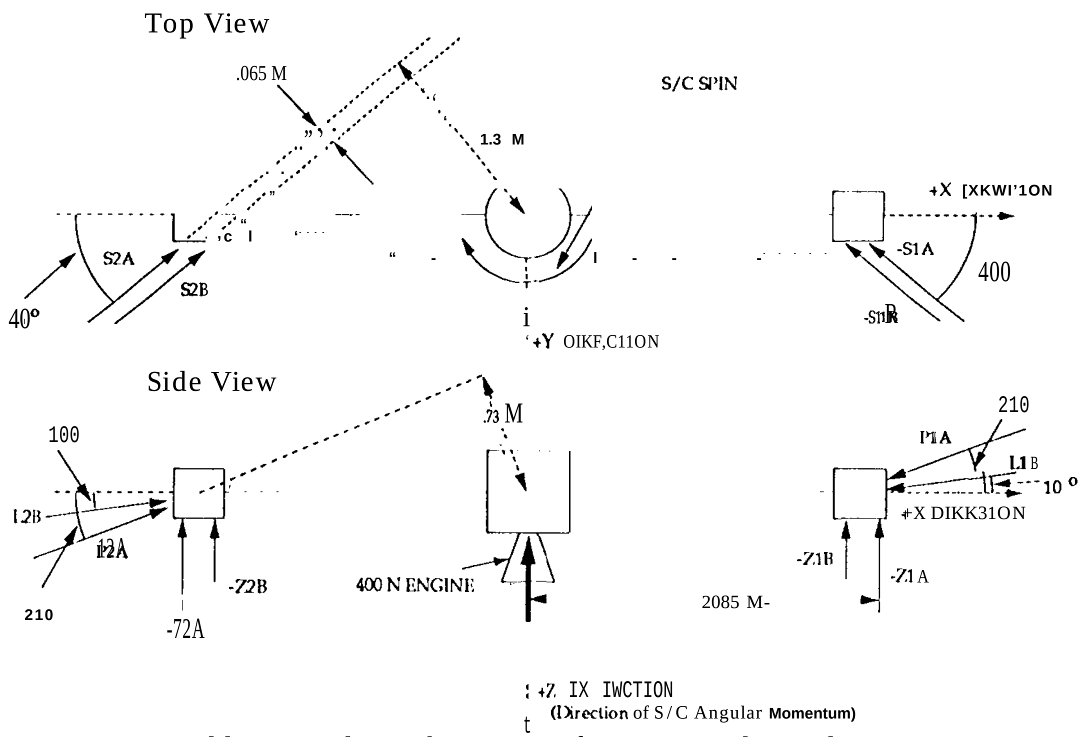


Figure 2: Galileo Propulsive Thruster Configuration and Coordinate Directions

For “vector mode” TCMS thc spacecraft does not changc orientation during the TCM activity. An arbitrary AV vector is implemented through the sequential firing of thc axial (-Z thrusters or P1 A thruster) and lateral (L1B and L2B) thrusters. The nearly orthogonal AV components form the desired AV vector. This mode can bc expensive in terms of propellant due to the sum of the components (rather than thc hypotcnusc) bcing implemented, as wcll as the high cost if the axial component happens to bc in the +Z direction. AV in the +Z direction is approximately 3 times more costly in terms of propellant than thc same AV in the -Z direction due to the 210 cant angle of the P1 A thruster. Implementation constraints, the operational advantages of not turning the spacecraft, and propellant cost usually determine when the vector mode strategy will bc used.

Almost without exception, in the absence of constraints, the optimum mode for maneuver implementation involves a reorientation of the spacecraft attitude, followed by a burn to complete the required velocity change. Reorientation of the spin axis is accomplished through gyroscopic action induced by thruster supplied torques. If the P-thrusters (1’1 A and P2A) are used to supply the torque, then the two thrusters are fired simultaneously, once pcr revolution of the spacecraft, to induce the desired precession. Since the two thrusters point in opposite directions, no net AV is imparted and the turn is referred to as a balanced turn. If two of the -Z thrusters are used to supply the torque, then alternating thrusters are fi rcd every half revolution of thc spacecraft to induce the desired precession. Since these two thrusters point in the samc direction, in addition to precession, there is a AV imparted to the spacecraft. This is rcferrcd to as an unbalanced turn and the applied AV must be considered in the design of the maneuver. Unbalanced turns are usually prcferrcd over balanced turns for the simple reason that the -Z thrusters have a moment arm about 3 timcs that of the P-thrusters and thus require less propellant for the same turn angle.

MANEUVER DESIGN GOALS

An important design goal of each TCM is to minimize the propellant required to complete the mission. Obviously, propellant is ncccssary for spacecraft navigation and therefore essential to achieving the mission objectives. The limited supply and high demand for propellant make it a very valuable consumable for the Galileo project. The Galileo propellant margin (PM) is defined to be the amount of usable propellant remaining at the 90% confidence level after completing the Jupiter orbital tour of tcn targeted satellite encounters. At launch, the PM was predicted to be -58 kg. Although this was a preliminary PM prediction made before the actual satellite tour selection, it identifies the motive to improve navigation strategies and usc propellant more efficiently. This goal is accomplished through increased usc of multi-mancuvcr trajectory optimization softwarc[5],[6], proper TCM planning (placement of TCMs, selection of aimpoints, implementation modes, etc.), and through accurate design of each particular AV that is to be executed by the spacecraft.

Accurate delivery of the spacecraft to each target is also an important goal for two primary reasons. In thc case of a gravity-assist flyby, small delivery errors are amplified into large errors manifested at the next encounter. As a result, it is important to minimize delivery errors in order to achieve the goal of minimizing propellant usage. An accurate flyby is also critical to the planned onboard science observation scqucncc. These science observations arc planned months in advance and depend upon the actual trajectory nearly duplicating the flyby geometry assumed in the design process. For example, the highest rcsolu tion asteroid images arc those taken nearest the asteroid and are therefore the most affected by a relative position error. A spacecraft time of flight delivery error can result in a significantly different asteroid direction with respect to the spacecraft at the scheduled time of the high resolution image. A large enough error could cause the camera to miss the asteroid. To avoid such scenarios, it is essential that the spacecraft delivery to each target be as accurate as possible.

Spacecraft navigation involves many statistical uncertainties that complicate the design of the perfect TCM. A TCM implements the AV that will correct an estimated state such that the spacecraft is placed on the desired trajectory for an upcoming encounter. The estimated state is obtained through the orbit determination process. This involves acquiring as much tracking data (radiometric and optical) as possible, accurately modeling all of the forces acting on the spacecraft, and then solving for the current trajectory which best fits, in a least squares sense, the acquired data. The solution state has a statistical uncertainty, described in terms of a covariance matrix, based upon the consistency of the tracking data. This uncertainty is combined with the uncertainty in the location of the encounter body itself (an ephemeris error) to produce the orbit determination uncertainty in the pre-TCM flyby conditions. This uncertainty describes the statistical errors expected from the orbit determination process. A second error source results from spacecraft AV mechanization, which is the translation of an ideal AV into discrete thruster pulses and an integer number of pulsing revolutions. Finally, the spacecraft itself dots not execute the ideal AV duc to the uncertainties of the state of the spacecraft (tank pressures, temperature, thrust levels, etc.) at the time of the design of the maneuver.

Since orbit determination and TCM execution errors arc usually estimated after performing the maneuver, spacecraft mechanization should be the only error source identifiable before the uplink of a TCM. This required proper modeling of the manner in which the Galileo spacecraft implements TCMS. Software tools have been developed and used to accurately simulate the pulsed mode implementation of Galileo TCMS. Each maneuver designed to date has accounted for the spacing of AV throughout the day of execution and the method by which each segment of a TCM is implemented. The accuracy of this process has been verified during the actual design of each TCM.

Another worthwhile goal is to provide a reliable and robust maneuver implementation strategy. This involves working closely with the spacecraft engineering team to incorporate their desires into the TCM design. For instance, turn and burn maneuvers maintain the proper burn at t i tude either from gyro information or by identifying the proper stars with the star scanner. identifying a good star set is preferable, as this avoids any gyro drift errors and is the normal mode of maintaining inertial reference during spacecraft cruise. Through interaction with the spacecraft engineering team, good star act attitudes arc identified in the proposed region of the sky for the TCM. With this information, the TCM design can generally accommodate a good star set for inertial reference at the burn attitude, thereby improving the reliability of the maneuver design.

MANEUVER DESIGN CONSTRAINTS

Maneuver design constraints which restrict or influence how the Galileo spacecraft performs the required TCMS can be divided into three broad categories: (1) trajectory design, (2) spacecraft and ground system capability, and (3) spacecraft safety and consumables conservation. Constraints within each of these categories have shaped the characteristics of TCMS throughout the VEEGA phase of the mission. The purpose of the discussion in this section is to identify and explain those constraints which affect the planning and design of TCMS and to discuss some of the rationale and history behind the implemented strategies.

Trajectory Design

The fundamental requirement of TCMS throughout the interplanetary phase of the mission is to deliver the spacecraft and probe to Jupiter. As mentioned previously, the circuitous VEEGA trajectory option made it possible to reach Jupiter with the current Galileo configuration using the IUS upper stage, and Jovian system science objectives specified an arrival date at Jupiter on December 7, 1995. The VEEGA trajectory option introduced a unique additional requirement for a planetary mission- the successful navigation of two flybys of the Earth. Project Galileo has taken advantage of the opportunity for additional science investigations enroute to Jupiter by electing to flyby two main belt asteroids, 951 Gaspra and 243 Ida. The discussion which follows addresses those constraints which influence how the prime mission objective (Jupiter) is achieved while satisfying the Earth navigation and asteroid flyby constraints. A successful strategy achieves the stated objectives with a minimum amount of propellant.

The two planned Earth encounters resulted in stringent navigation requirements as a consequence of the spacecraft's electrical power source, radioisotope thermoelectric generators (RTG's). Extensive pre-launch analysis resulted in a plan for navigating the spacecraft through the two Earth flybys and is detailed in References [71 and [81. This strategy was developed to ensure that the risk of Earth impact by the spacecraft due to both navigation activities and spacecraft and ground failures is negligible. A summary of the major groundrules follows

(1) All TCMS between launch and the second Earth Gravity Assist (Earth 2) will be designed so that the probability of being on an Earth impacting trajectory following the successful completion of a TCM is less than $1x10^{-6}$. As a further constraint, it is also required that if the maneuver were to terminate during execution inadvertently, the resulting trajectory must also satisfy the same $1x10^{-6}$ constraint.

(2) While the spacecraft is in the asteroid belt, the trajectory shall be designed such that if an unplanned AV occurs as a result of a collision with an asteroidal micrometeroid, the AV will not be sufficient to place the spacecraft on an Earth-reentry trajectory. For the purpose of defining an asteroid belt constraint region, this requirement was specified in the form of a AV bias of 3 m/s over the time period from July 2, 1991 through August 4, 1992. Figure 3 shows this target constraint region in the Earth 2 encounter aiming plane, or b-plane (see Appendix). The figure shows the region inside of which the spacecraft could not be targeted upon entry into the asteroid belt (i.e. the constraint region for TCM-10 design). On July 2, 1991, the 3 m/s constraint region was very long and narrow. Over time, the semi-major axis of the 3 m/s constraint region decreased significantly while the semi-minor axis increased slightly. This resulted in a more circular constraint region on August 4, 1992.

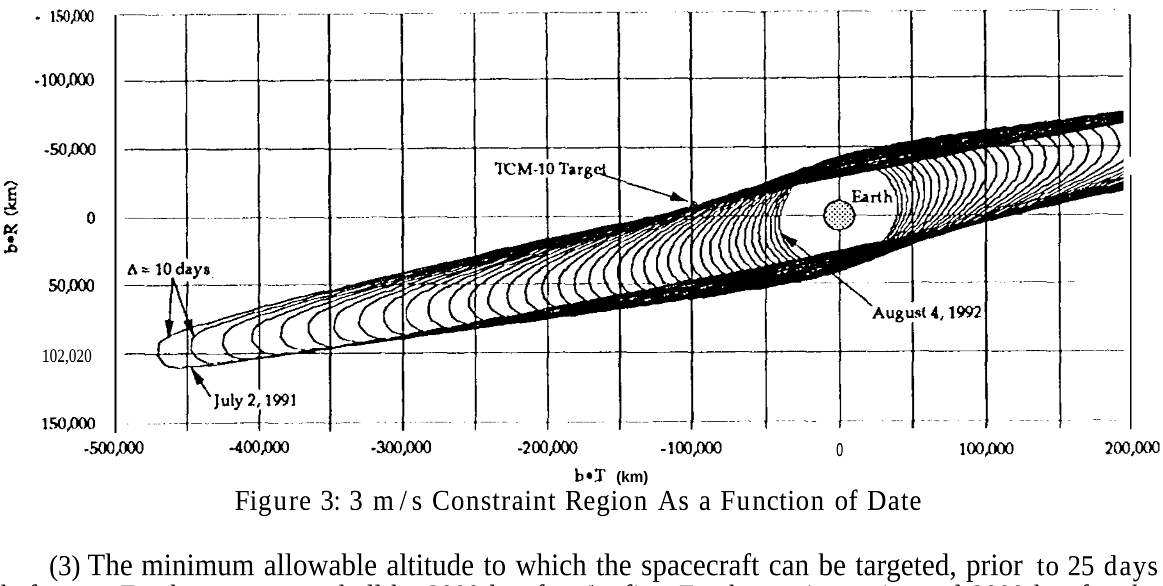


Figure 3: 3 m/s Constraint Region As a Function of Date

(3) The minimum allowable altitude to which the spacecraft can be targeted, prior to 25 days before an Earth encounter, shall be 3000 km for the first Earth gravity assist and 2000 km for the second Earth gravity assist. The minimum allowable flyby altitude shall be 300 km.

(4) After 10 days before an Earth encounter, no thruster firings, other than those required for spin maintenance and pointing corrections, arc to be performed.

A result of the navigation strategy development prior to launch was the placement of the TCMS on each approach to Earth. The approach TCMS were placed at 60 days (TCMs 6 and 15), 25 days (TCMs 7 and 16), and 10 days (TCMs 8 and 17) prior to each Earth encounter. The location of these TCMS was a fundamental input in the navigation strategy development. As such, their location would not change after launch. Each of these maneuvers was part of an Earth aimpoint biasing strategy designed to accommodate the requirements mentioned above. The -60 day TCMS were targeted to the altitude constraint specified in (3), At the -25 day epoch, the aimpoint required to achieve the proper flyby geometry and gravity assist was targeted. Execution and orbit determination errors at the time of the -25 day TCMS were too large to leave uncorrected, so small TCMS at -10 days were required to reduce the miss and the downstream propellant requirements. These TCMS will be discussed in more detail in a later section.

item (2) in the above list of constraints directly resulted in the placement of a TCM at the beginning of the asteroid belt constraint time span (TCM-1O on July 2, 1991) and at the end of the time span (TCM-14 on August 4, 1992). TCM-1 O was targeted to the desired Gaspra aimpoint (while at the same time moving the Earth 2 aimpoint outside of the 3 m/s constraint region). The TCM-10 aimpoint with respect to the Earth constraint region is shown in Figure 3. All TCMS in the asteroid belt satisfied the Gaspra and Earth target constraints. Immediately upon "exit" from the asteroid belt, the 3 m/s constraint no longer applied, and TCM-14 was targeted to the first in a series of biased Earth aimpoints satisfying the $Ix10^{-6}$ Earth impact probability and the altitude constraints.

Figure 3 is just one example of a next-body constraint. During those periods of time when the next encounter was Earth (Launch to Venus and Earth 1 to Gaspra phases), aimpoints at the upcoming encounter body propagated to the subsequent Earth encounter were required to satisfy the $1x10^{-6}$ constraint. A good example of how this constraint was applied was in the design of TCM-1, just after launch. TCM-1 was a large maneuver that was targeted to Venus (- 16 m/see) with significant execution errors expected. The expected distribution of errors, when mapped to the subsequent Earth 1 encounter, showed that the probability of impact would be greater than 1X10-6 if the optimal aimpoint at Venus was targeted, As a result, the aimpoint at Venus for TCM-1 was biased such that the probability of impact at Earth was sufficiently reduced. In addition, the order of the vector mode segments (axial segments followed by lateral segments) was such that the path of the maneuver in the Earth 1 b-plane never crossed the $1x10^{-6}$ constraint region, thus satisfying the second part of the constraint summarized in (1) above. The ability to reverse the order of implementation of segments was included as a pre-launch capability to help satisfy the path constraint specified in (1). No TCM in flight required the segment order to be reversed. Details of the implemented maneuvers arc discussed in a later section.

Spacecraft and Ground System Capability

Among the constraints on the design of TCMS arc those duc to the capabilities of the spacecraft and the ground system which operates the spacecraft. These types of constraints result from hardware, software, staffing and budget constraints. To understand how each of these factors can influence the design and planning of a TCM, the process of implementing a AV on the spacecraft and the activities required leading up to that implementation must be explained.

The maneuver design process begins with an error analysis of the nominal trajectory design. This analysis results in a candidate set of TCM locations throughout the mission. Maneuver placement may result from trajectory design constraints, as discussed earlier, or from a statistical analysis of the errors which perturb the nominal trajectory. Aftcr a candidate set of maneuver locations has been identified, the plan is discussed with mission planners who will integrate the maneuver request with other activity requests from the various flight teams. Some of thc problems which can force a maneuver away from the requested date include DSN tracking availability, tclecom capability, critical science activit ics and staffing limitations. TCM-19 is an example where a TCM was delayed a week to avoid a conflict with science activities at solar opposition. TCM-21 is an example where a TCM will be delayed by 1 day from -3 days to -2 days, relative to Ida, due to a tracking conflict. In this example the Mars Observer mission orbit insertion maneuver occurs during the same time frame as the Galileo Ida cncountcr. After a day has been identified in the sequence, a period of time is reserved exclusively for the TCM activities. This TCM window is sized such that the ncccssary changes in spacecraft configuration can bc completed and the predicted amount of AV can be implemented. Any scqucncc which contains a TCM activity must have a portion of the Command and Data Subsystem (CDS) memory reserved for the activity. This memory, referred to as a High Lcvcl Module (HLM) box, limits the number of activities that can be performed within a TCM window.

TCM implementation for Galilco is a complex and time consuming activity on the spacecraft. As mentioned previously, thc 10 Newton thrusters are operated in pulsed mode, Because of thruster operation constraints and attitude and spin perturbations, only a limited number of pulscs can be performed before spin and attitude corrections are required. As a result, the AV to be implemented in a single day must be broken up into small segments, each typically separated by an attitude correction and / or spin correction. Each of the activities uses memory and takes a significant amount of time to complete (typically about 20 minutes pcr attitude correction or spin correction). Because the whole TCM activity (including commands to warm-up gyros, configure heaters, etc.) must fit within 1 HLM box (853 bytes during cruise), and the TCM must be monitored by onc shift (typically 8-10 hours) on the ground, the amount of AV pcr day must necessarily be limited. TCM-14 illustrates how these constraints affect the maneuver design. The total required AV for TCM-14 was approximately 21 m / s. The constraints specified above limited the AV that could be implemented in a single day to just over 6 m / see. As a result, this particular TCM required four days (or portions) of activity to implement the required AV. The planning for a multi-portion TCM must take place wcll ahead of time to accommodate the tracking and staffing requirements for such a high activity event. Another constraint limiting the amount of AV pcr day has to do with the recording of engineering data on the spacecraft tape recorder during a TCM. The post-Venus maneuvers (TCM-4A for example) were required to be recorded on the onc track left available for recording engineering data. (The other three tracks were fillcd with the Venus cncountcr science data.) This limited the mancu vcr duration to eight hours per day for each of the required four days.

A factor which can significantly affect how a TCM is designed and how propellant consumption is predicted relates to the process of sequence development. The mission planners and scqucncc developers need a significant amount of lead time (sometimes 6 to 9 months) to design and develop the encounter observation sequences in support of the varied science objectives. As a result there is a preference for fixing the aimpoint at an encounter body (an aimpoint about which all planning can occur) significantly in advance of the event regardless of the propellant costs. Needless to say, a balance must bc struck in which targeting flexibility is permitted up to an agreed upon point in time, after which encounter targets must not change. This type of constraint must be accounted for in the planning process (both propellant estimation and sequence development) to avoid unplanned propcllant expenditure or rework of sequences. This constraint is very significant in the planning for orbital operations at Jupiter.

Maneuver placement must account for the time it takes to develop the proper commands for TCM execution after all available tracking data has reached the ground. The templates for designing TCMS contain the ordered allocations of time required by each of the flight teams to complete their assigned task accurately. The template is most important for encounter TCMS where accurate maneuvers or quick clean-up maneuvers are critical. The encounter-relative time at which the tracking data is cutoff is typically the most important factor in determining the flyby accuracy. The later the cutoff, the better the accuracy. If there arc stringent flyby accuracy requirements, this might dictate a cutoff of tracking data very close to the encounter (immediate and nonstop design of a critical TCM) with uplink and execution of the maneuver occurring just days prior to encounter. This is indeed the plan for TCM-21 which will occur on August 26,1993, just 2 days before the Ida encounter. Such high speed maneuver design in combination with the late data cutoff allows the science observations to be planned without the requirement for a late sequence tweak of the scan platform pointing parameters.

Spacecraft Safety and Consumables Conservation

Typical of any mission arc those constraints which protect science instruments and engineering hard ware from environments for which they were not designed. Chief among these for Galileo are sun-viewing constraints for science instruments and off-sun angle (angle between HGA bore-sight and sun direction) restrictions for thermal control of sensitive components. Illumination of a detector or shutter by direct or reflected sunlight can damage or destroy an instrument, and excessive heating can damage the probe, thermal control louvers or a multitude of other instruments. Since a typical trajectory correction ΔV vector could be in an arbitrary direction and could quite easily be accomplished by turning the spacecraft in the direction of the desired ΔV vector and firing the thrusters, there must be constraints to protect the instruments and restrict such turning. As an example, solid state imaging (SS1) viewing constraints prohibit any attitude in which the angle between the solar disc and the optical axis is less than 20”, while the spacecraft is within 5 AU of the sun. This constraint is applicable at all times, including during the turn to a TCM burn attitude. This is just onc example of many such constraints imposed by the various instruments and systems. TCM planning and design must account for each of these constraints.

One of the modifications to the Galileo spacecraft for the VEEGA trajectory was the addition of a large sunshade to shield the bus from the sun while the spacecraft traveled in the inner solar system. In order for the sunshade to work, the spacecraft attitude had to bc constrained to be nearly sun pointed throughout much of the VEEGA trajectory. As a consequence, all TCMS within 1 AU of the sun were required to be implemented in vector mode (no turns allowed during the TCM). As mentioned previously, this can bc expensive in terms of propellant. As a result of the cost associated with the vector mode constraint, a strategy of placing two TCMS after each of the planetary encounters (Venus, Earth 1, Earth 2) was adopted. The first TCM after the encounter was placed relatively close to the flyby while the second was placed at approximately 1 AU so that the maneuver could be planned to bc accomplished using a turn mode. This strategy allowed for optimal allocation of AV between the two post encounter maneuvers, while accounting for the vector mode restriction of the first maneuver.

Careful operation of the spacecraft is of paramount importance. Any first-time activity on the spacecraft is necessarily viewed as a risk and undergoes significant scrutiny. Whether or not the activity has been previously tested on the ground, the maneuver design philosophy of the project during the VEEGA phase of the mission has been to increase the ground and spacecraft implementation complexity slowly while gaining an understanding of the spacecraft behavior. As more experience has been gained flying the spacecraft, more capabilities have been exercised allowing for increased flexibility in the design of TCMs. To illustrate this philosophy, a sequence of propulsive maneuver events is presented below showing a gradual increase in maneuver implementation capability.

Event	Execution Date	Comment
TCM-4B	11-May-1990	First scheduled unbalanced turn TCM. Actually implemented using vector mode.
Unbalanced Turn	07-Jan-1991	First usc of the unbalanced turn mode. Turn angle= 7°.
TCM-9B	20-Mar-1991	Second scheduled unbalanced turn TCM. Actually implemented using vector mode.
TCM-10	02-Jul-1991	First turn TCM. Used balanced turns. Celestial reference required at the burn atti tude.
Unbalanced Tum	21-Jul-1992	Large turn using the unbalanced turn mode. Turn angle = 30°.
TCM-19	09-Mar-1993	First unbalanced turn TCM. First TCM to rely exclusively on gyros for attitude reference, (Planned mode for majority of TCMS at Jupiter.)

Of particular interest in the above sequence of events is how the capability to implement turn maneuvers was slowly developed: In January '91 a small unbalanced attitude control maneuver, in July '91 a small balanced turn to an attitude with good stars for celestial reference followed by a lateral burn, in July '92 a large unbalanced turn to an attitude with celestial reference, and finally in March '93 an unbalanced turn and a -Z burn using gyros exclusive] y. TCM-19 represents the method of maneuver implementation that will be relied upon during the orbital operations phase at Jupiter.

Propellant is the most important of consumable items on the spacecraft for navigation. However, there are other consumables besides propellant which can influence the mode selected to implement a desired AV. As mentioned earlier, the thrusters are operated in pulsed mode and each thruster has been qualified for 35,000 pulses. This qualified limit results in the consumable tracking of thruster pulses. The lateral thrusters have been heavily used during TCMS and have accumulated just over 9300 pulses on each lateral thruster (27% of lifetime). Although there is not a concern for overuse at this time, it is prudent in situations where the cost is not significant to use the -Z thrusters, thus distributing thruster pulses more evenly among the various thruster types. Attitude control requirements anticipate a significant accumulation of thruster pulses on the P-thrusters (I'1 A and P2A). *In* the interest of conserving propellant and thruster pulses on the P-thrusters, those attitude control turns which can be anticipated far in advance and accounted for in the design of TCMS are being implemented in an unbalanced mode using the -Z thrusters. In this mode, turn costs are reduced by almost a factor of 3 and the pulses are implemented by the redundant -Z thrusters (at a cost of increased ground system complexity to account for the additional propulsive maneuvers).

Another consumable being tracked is the number of tape recorder start/stop cycles. Telecom visibility during TCMS has not been a significant issue in the design of any TCMS to date. Unlike a mission such as Voyager, every TCM executed has been visible via telemetry and Doppler. Future planning calls for a significant number of TCMS to be executed without the benefit of such complete telecom visibility. As a result, engineering telemetry must be recorded for those TCMs. Again, if the cost is not significant, it is desirable to choose an implementation mode with telecom visibility during the bum and avoid the additional start /stop cycles on the tape recorder.

RESULTS

A listing of all interplanetary TCMS through Jupiter orbit insertion is provided in Table 1. It is evident from this table that "vector" is the most common mode for TCM implementation in the interplanetary phase. This is due in part to the sun-point strategy for thermal protection as well as the numerous small statistical maneuvers which occur before each encounter. The table also documents that interplanetary maneuvers which required an inertial AV (AVi) greater than 6 m/s used multiple portions. The total AV (ΔVt) represents the velocity change equivalent to the amount of propellant used (AM). It includes implementation costs of vector mode maneuvers, thruster penalties, AV bum arc loses due to the spinning spacecraft, and turn costs if any. Ideally, the difference between the inertial and total AV should be kept as small as possible. The AV estimates were reconstructed via the orbit determination process. The last two columns document the changes in both the b-plane and time of closest approach at the target body as a result of an ideal TCM implementation.

Table 1: Interplanetary TCM Profile

Event	Date	Location (Days)	Mode	Portions	ΔVi (m/s)	+Z (m/s)	-Z (m/s)	L (m/s)	ΔVt (m/s)	Δb (km)	ATCA (h:mm:ss)
Injection	19-Oct-89										
TCM-1 DSM	9-Nov-89	Inj.+21	Vector	3	15.93		15.86	1.79	17.69	152,933	-5:53:51
TCM-2	22-Dec-89	Inj.+64	Vector	1	0.75	0.17		0.73	1.21	1,922	-0:03:29
TCM-3	29-Jan-90	V-12	Cancelled								
Venus	10-Feb-90										
TCM-4A DSM	9-Apr-90	V+58	Vector	4	24.18			24.18	24.66	1,929,897	-21:14:02
TCM-4B DSM	1 1-May-90	V+90	Vector	2	11.03			11,03	11.25	498,212	-81800
TCM-5	17-Jul-90	E1-144	Vector	1	0.93		0.74	059	1.34	20,117	-0:29:58
TCM-6	9-Oct-90	E1-60	Vector	1	0.51		0.48	0.19	0,6s	2,453	-0:0512
TCM-7	13-Nov-90	E1-25	Vector	1	1.28		1.10	0.67	1.79	2,43S	-0:04:04
TCM-8	28-Nov-90	E1-10	Vector	1	0.05	0.02		0.05	0.11	47	0:00:02
Earth 1	8-Dec-90										
TCM-9A	19-Dec-90	E1+11	Vector	1	5.27			5.27	5.38	203,440	-12:56:06
TCM-9B	20-Mar-91	E1+102	Vector	1	2.30	0.20		2.28	2.89	23,784	1:15:12
TCM10 DSM	2-Jul-91	G-119	Turn/Bum	1	3,62			3.62	4.22	32,576	-0:24:55
TCM-11	9-Oct-91	G-m	Vector	1	0.35	0.09		0.34	0.59	581	-0:00:24
TCM-12	24-Oct-91	G-5	Vector	1	0.33		0.05	0.32	0.38	144	0:00:03
Gaspra	29-Oct-91										
TCM-13	21-Nov-91	G+23	Cancelled								
TCM-14 DSM	4-Aug-92	E2-126	Vector	4	21.23		0.42	21.24	22.08	68,939	7:44:00
TCM-15	9-Oct-92	E2-60	Vector	1	0.72		0.40	0.61	1.02	2,969	-0:05:06
TCM-16	13-Nov-92	E2-25	Vector	1	0.89			0.89	0.91	1,882	-0:01:14
TCM-17	28-Nov-92	E2-10	Vector	1	0.03		0.02	0.02	0.05	15	-0:00:03
Earth 2	8-Dec-92										
TCM-18	21-Dec-92	E2+13	Cancelled								
TCM-19	9-Mar-93	E2+91	Turn/Burn	1	2.12		2.12		2.12	19,673	0:39:49
TCM-20	13-Aug-93	Ida-15	Vector	1							
TCM-21	26-Aug-93	Ida-2	Vector	1							
Ida	28-Aug-93										
TCM-22 DSM	4-Oct-93	Ida+37	Vector	5	38						
TCM-22A	15-Feb-94	J-660	Vector	1							
TCM-23	12-Apr-95	J-239	Valor	1							
TCM-24	23-Jun-95	J-167	Vector	1							
Probe Release	10-Jul-95	J-150									
TCM-25 ODM	17-Jul-95	J-143	400N	1	58						
TCM-26	29- Aug-95	Io-100	Vector	1							
TCM-27	17-Nov-95	Io-20	Vector	1							
TCM-28	27-Nov-95	Io-10	Vector	1							
TCM-28A	2-Dec-95	Io-5	Vector	1							
Io/Jupiter	7-Dec-95										
TCM-29 JOI	7-Dec-95	J+0	400N	1	645						

DSM . Deterministic Deep-Space Maneuver

Table 2 lists the spacecraft mechanization errors and orbit determination estimates of the execution errors for each TCM. The spacecraft mechanization errors have generally been very small with a mean magnitude error of +0.21% and a mean pointing error of 1.67 mrad. These errors have never been a significant error source in the TCM delivery accuracy. The TCM execution errors are estimated after obtaining navigation tracking data and solving for the maneuver. The result is compared to the engineering design ΔV to determine execution errors. It is interesting to note that the observed 1.2% standard deviation in TCM magnitude errors exactly agrees with pre-launch models.

Table 2: Spacecraft Mechanization and TCM Execution Errors

	Ideal ΔV	Mech. Errors		Engineering Design ΔV			TCM Execution Errors: Magnitude (%)				TCM Execution Errors: Direction (mrad)			
TCM	(m/s)	Msg. (%)	Dir. (mrad	+Z (m/s)	-Z (m/s)	L (m/s)	+Z	-Z	L	Tota	+Z	-Z	L	Tota
'KM-1	15.65	+0.12	0.15		15.60	1.74		+1.6	+3.3	+1.7		12.3	8.3	10.9
TCM-2	0.74	+0.06	0.76	0.16		0.72	+2.4		+2.2	+2.1	32.9		11.7	7.4
TCM-4A	24.74	+0.02	0.48			24.75			-2.3	-2.3			5.4	5.4
TCM-4B	11.27	+0.09	0.34			11.28			-2.2	-2.2			8.5	8.5
KM-5	0.92	+0.14	0.56		0.72	0.59		+2.5	-0.2	+1.4		3.0	2.4	15.1
TCM-6	0.51	+0.04	0.52		0.48	0.19		+0.8	-1.6	+0.3		0.2	6.3	8.1
TCM-7	1.26	+0.16	2.08		1.09	0.67		+1.2	+1.3	+1.5		8.7	6.1	9.7
TCM-8	0,05	+0.14	2.74	0.02		0.05	+1.2		-0.6	-0.4	1.7		2.8	5.6
TCM-9A	5.28	+0.03	0.13			5.29			-0.3	-0.3			8.2	8.2
TCM-9B	2.28	+0.10	0.24	0.20		2.27	+0.5		+0.6	+0.5	5.0		5.3	5.6
TCM-10	3.65	+0.20	0.17			3.65			-0.9	-0.9			12.8	12,8
TCM-11	0.35	+0.21	0.43	0.09		0.34	+0.4		+0.0	+0.0	0.1		1.7	0.8
'KM-12	0.33	-0.30	0.70		0.05	0.32		+0.6	-0.5	-0.5		1.1	4.3	3.8
'KM-14	20.95	+0.06	0.52		0.41	20.%		+2.7	+1.3	+1.3		4,8	9.5	9.6
'KM-15	0.72	+0.12	0.39		0.40	0.61		+0.4	+0.7	+0.6		2.9	0.9	2.5
TCM-16	0.89	-0.07	6.69			0.89			-0.3	-0.3			10.2	10.2
TCM-17	0.03	+2.45	13.11		0.02	0.02		+0.0	+0.0	+0.0		0.1	0.3	0.1
TCM-19	2.12	+0.16	0.07		2.12			-0.2		-0.2		0.8		0.8
	Mean =	+0.21	1.67						Mean =	+0.1			Mean =	7.0
	Std. Dev. =	0.56	3.17						Std. Dev. =	1.2			Std. Dev. =	4.1

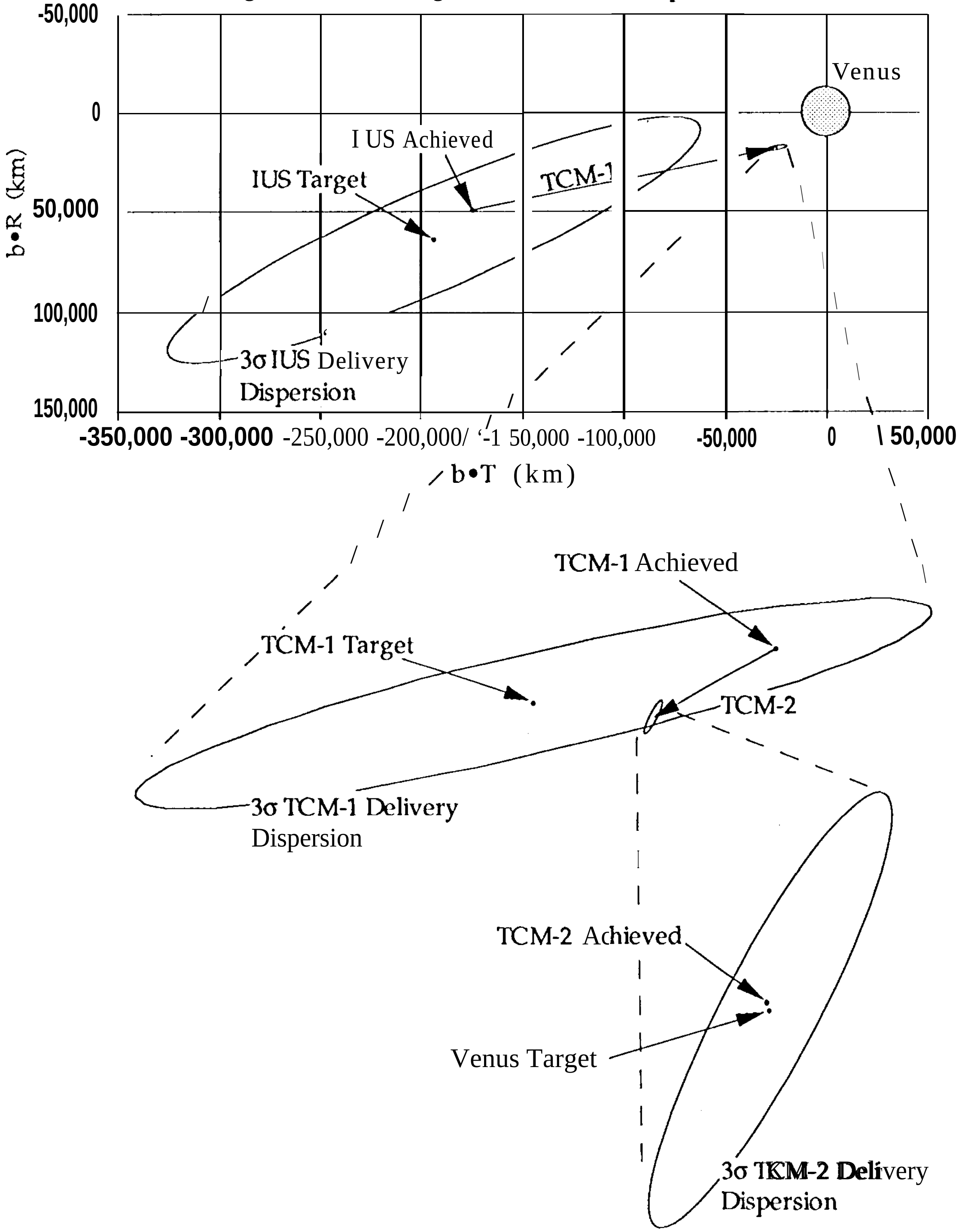
A brief description follows of the different trajectory legs and some of the unique characteristics of each TCM.

Launch to Venus

After two delays and despite foul weather predictions, the Galileo spacecraft experienced a near-perfect launch onboard the Space Shuttle Atlantis on October 18, 1989. Six and a half hours later, the spacecraft and IUS were deployed from the shuttle cargo bay. The first of two IUS solid rocket motor firings occurred an hour later to initiate an extremely accurate interplanetary injection, as can be seen in Figure 4. The Galileo spacecraft achieved an Earth-departure with a hyperbolic excess velocity of 3.93 km/s. The IUS target was biased from the final aimpoint at Venus as a result of a TCM-1 strategy developed prior to launch.

TCM-1 was constrained to be a vector mode maneuver at a sun-pointed attitude required for thermal protection. The maneuver was placed 21 days after injection to correct injection errors and also to remove a 17 m/s bias built into the IUS target.[9] This aimpoint bias was necessary to avoid the possibility (99% protection) of performing a large statistical maneuver using the ΔV-inefficient P1 A thruster. The TCM-1 aimpoint required a small bias as well, in order to satisfy the 1×10^{-6} probability of impact for Earth navigation, As this was the first TCM executed by Galileo, the maneuver segments were designed assuming 3σ worst case thruster misalignments. This assumption resulted in AV maneuver segments with very few pulsing revolutions before a pointing and spin correction would occur. The thruster misalignments turned out to be very small, and subsequent maneuvers were designed using two to three times more pulsing revolutions per segment.

Figure 4: Venus Target and Achieved **Aimpoints**



TCM-2 targeted to the final Venus aimpoint and provided the first opportunity to characterize the +Z thruster. There was sufficient flexibility in the selection of the Venus aimpoint to allow for the deliberate design of a maneuver with a + Z AV component. It was desirable to observe the PI A thruster characteristics in cruise rather than possibly rely upon it for the first time just 12 days before the Venus flyby at TCM-3. TCM-2 was also the first and only time to date that larger "standard" pulse widths were used. For the lateral thrusters, this meant doubling the pulse width from 1.3 to 2.7 seconds. This was done to characterize thruster performance and temperature behavior using the longer burn durations. Since the longer pulse widths result in greater thermal stresses to the thrusters, all subsequent TCMS have used the shorter, "benign" pulse widths.

TCM-3 was planned to correct any remaining trajectory errors prior to the Venus gravity assist. The orbit determination estimate at the time of the maneuver design had a one sigma uncertainty that encompassed the Venus target. Consequently, there was little or no benefit to performing this maneuver, and it was canceled. This proved to be the proper decision. In fact, if TCM-3 had been performed, it would have made the Venus delivery error worse rather than better. Reconstruction of the Venus flyby revealed that the spacecraft came within 9.6 km of the Venus aimpoint at a closest approach time just 18 seconds earlier than the target time.[10] The gravity assist increased the spacecraft's heliocentric speed by 2.2 km/s and provided the flight team with their first encounter opportunity. Galileo was placed on a return path to the Earth with three of the four tracks of tape filled with Venus encounter science data.

Venus to Earth 1

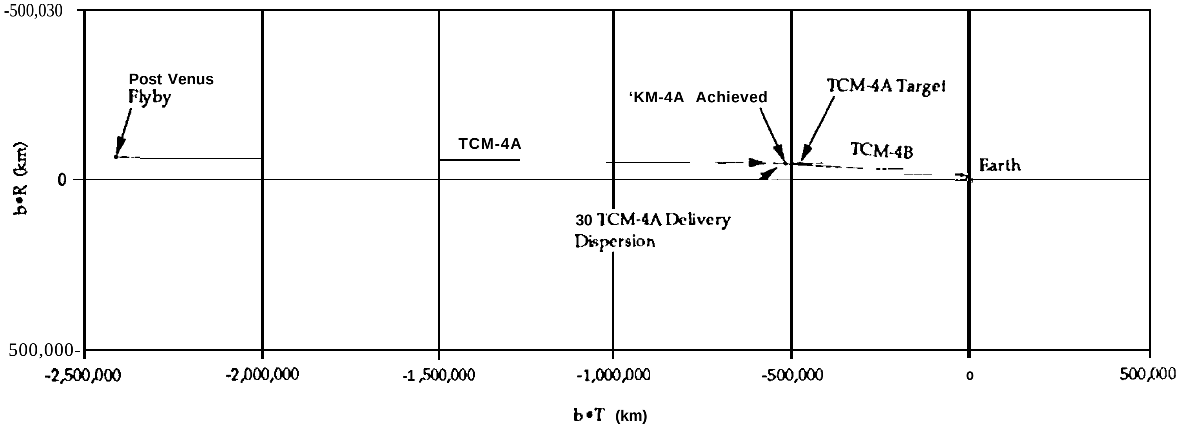


Figure 5: TCM-4 Deep Space Maneuver

A deep space maneuver (DSM), TCM-4, was required after Venus to return to Earth for the' first of two Earth gravity assists. A DSM is a deterministic AV required to reach the final destination. To satisfy the spacecraft thermal constraints and save propellant, TCM-4 was divided into two parts, TCM-4A and TCM-4B (see Figure 5). The first part was soon after Venus, and therefore needed to be done vector mode to maintain a sun pointed attitude for thermal protection. The second part was executed when the spacecraft reached a heliocentric distance of 1 AU. At this solar distance, the thermal constraints allowed for turning of the spacecraft to perform the TCM. In effect, the strategy was to perform as much of the velocity change as soon as possible, and delay that part of the velocity correction which could be done for less propellant when vector mode costs could be avoided.

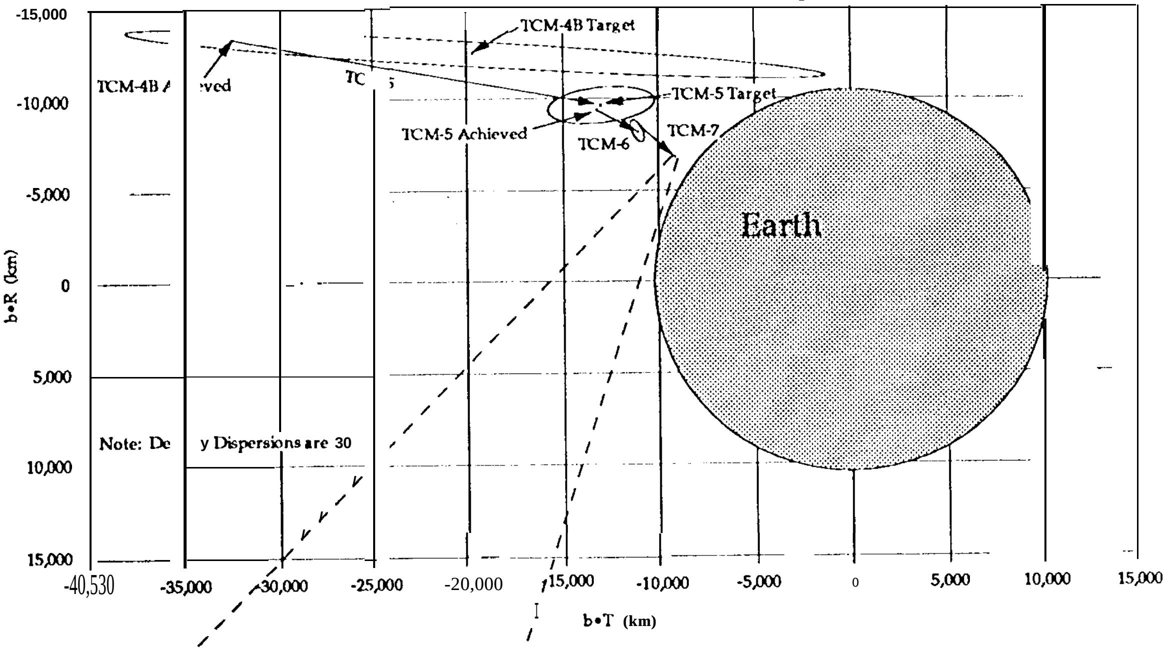
Preliminary TCM-4A designs revealed that by increasing the AV magnitude of TCM-4A and decreasing the magnitude of TCM-4B, both maneuvers would require only the lateral thrusters for the proper velocity correction. For a cost of 0.3 kg of propellant, the flight team would be able to postpone the testing of unbalanced turns. The option of making both TCM-4A and 4B purely lateral maneuvers was approved and thus delayed the first time activity of a turn and burn maneuver. in order to make TCM-4A a purely lateral maneuver, the spacecraft engineering team, for the first time, had to delete the residual axial AV commands which resulted from the engineering design process on the ground. This was a strategy later to be used by TCMS 4B, 9A, and 16.

TCM-4B finished the trajectory correction that TCM-4A had begun. This TCM could only place the trajectory as close to the Earth as the 1X10-6 Earth navigation constraint would allow. Due to TCM-4A delivery errors, TCM-4B was required to make use of the flexibility in the Earth closest approach time to maintain the purely lateral maneuver strategy. The time of flight was adjusted 11 minutes earlier at a small deterministic cost of 0.1 kg.

The next three maneuvers, TCMS 5,6, and 7, moved the trajectory progressively closer to the Earth and the final aimpoint, in accordance with the Earth navigation strategy (see Figure 6). Like the maneuver before it, TCM-5 was restricted in how close it could target to the Earth by the 1 xl 0^{-6} probability of impact constraint, The size of this constraint region was dependent upon the expected delivery errors after maneuver execution. A primary error source was the orbit determination accuracy at the time of each maneuver design. As the spacecraft traveled closer to the Earth, the orbit determination knowledge improved, resulting in a smaller constraint region. The trajectory was then safely moved closer to the Earth by TCM-5. Sixty days before the first Earth gravity assist, the limiting constraint was no longer the 1 xl 0^{-6} probability of impact, but rather the 3,000 km altitude constraint in force up to 25 days before closest approach. TCM-6 met this constraint with some pad by targeting to an altitude of 3,125 km. As soon as the time to go allowed it, TCM-7 at Earth 1-25 days was targeted to the desired aimpoint altitude of 952 km. This TCM placement satisfied the Earth navigation constraints at minimum propellant cost.

TCM-8 provided a final opportunity to clean-up the Earth delivery just 10 days before closest approach. This maneuver was necessary to provide an accurate gravity assist and avoid a 41 m/s cost due to a flyby altitude which was projected to be, coincidentally, 41 km too low. Figure 7 is the Earth 1 mission cost contour. The cost contour plot is useful for estimating downstream costs as a function of two-dimensional b-plane errors. It is very accurate when time of flight errors have little effect on downstream costs, as was the case with Galileo's two Earth gravity assists. The indicated point on the contour shows that the TCM-8 delivery was just 9 km from the ideal aimpoint, while the time of closest approach was late by only 0.4 seconds.[10] Unfortunately, the 9 km aimpoint error translated into an 8 km altitude error which was in nearly the direction of maximum cost. The same miss in a more favorable direction would have only cost 1-3 m/s. The actual miss shown in Figure 7 resulted in a cost of approximately 7.6 m/s, to be corrected for the most part by the post Earth 1 statistical maneuvers, TCMS 9A and 9B. The Earth 1 gravity assist added 5.2 km/s to the spacecraft's heliocentric speed and increased the orbit period to two years.

Figure 6: Earth 1 Target and Achieved Aimpoints



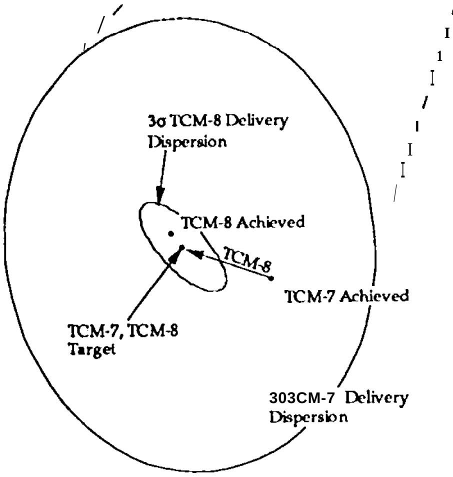
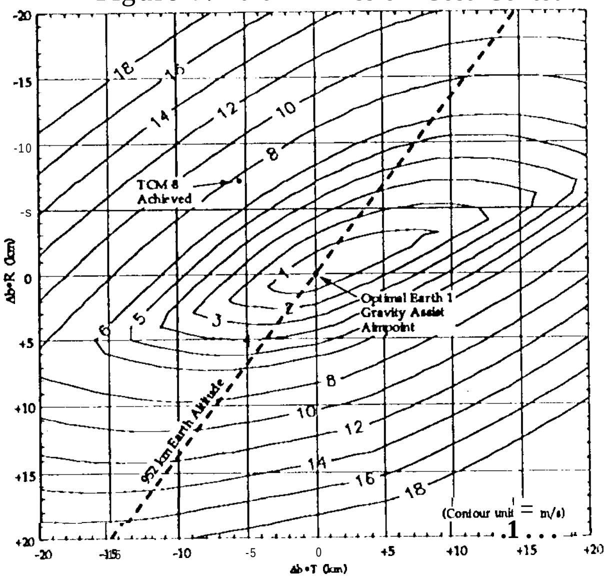


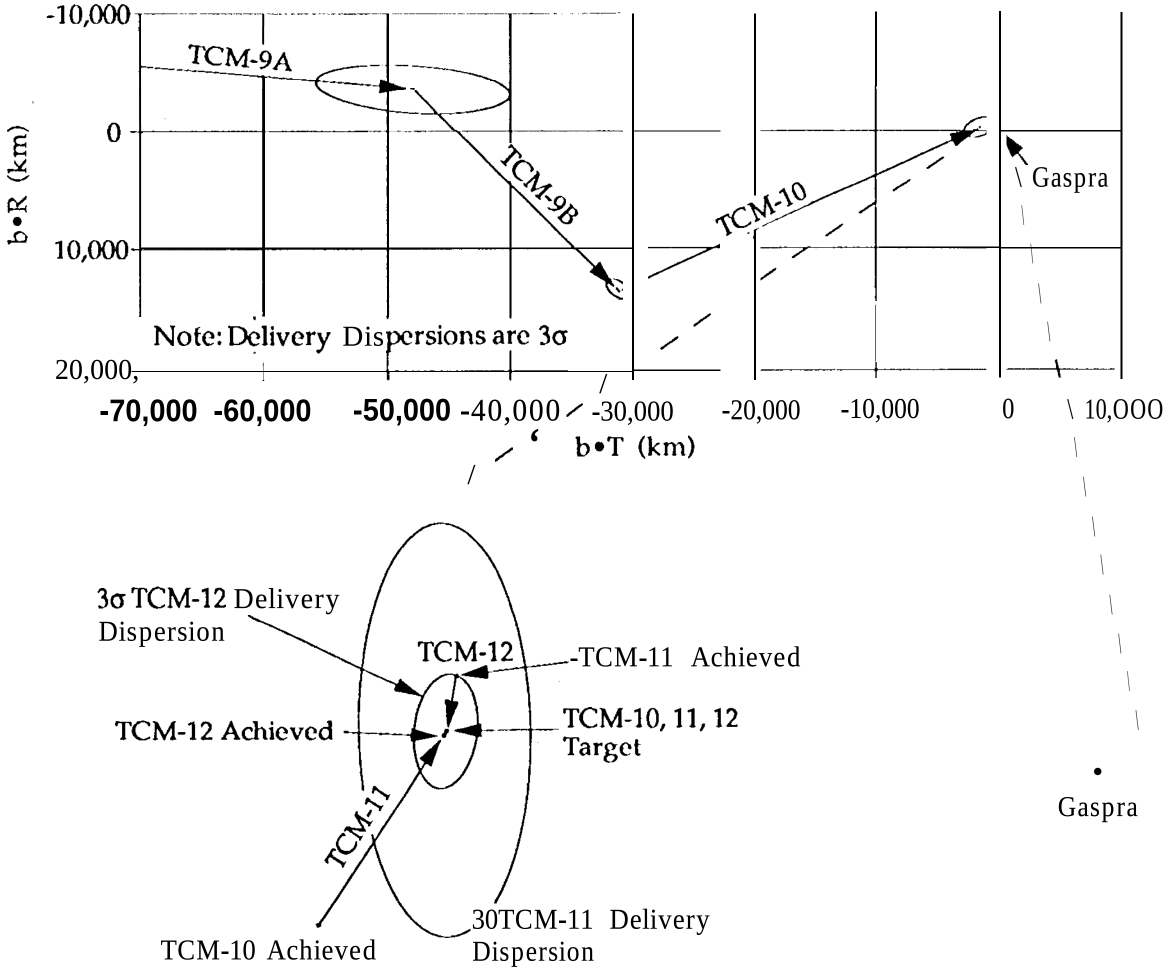
Figure 7: **Earth 1 Mission Cost Contour**



Earth 1 to Gaspra

The next three TCMS, 9A, 9B, and 10, were used to correct the Earth gravity-assist errors, provide the 3.5 m/s deterministic correction needed to get to Gaspra, and at the same time satisfy the 3 m/s AV bias from an Earth impacting trajectory upon entering the asteroid belt. Consequently, it was not satisfactory simply to target to the final desired aimpoint at Gaspra. In this situation the direction of the incoming asymptote had to be designed to control the trajectory at the subsequent encounter with the Earth. This resulted in a peculiar looking path to Gaspra as seen in Figure 8.

Figure 8: Gaspra Target and Achieved Aimpoints



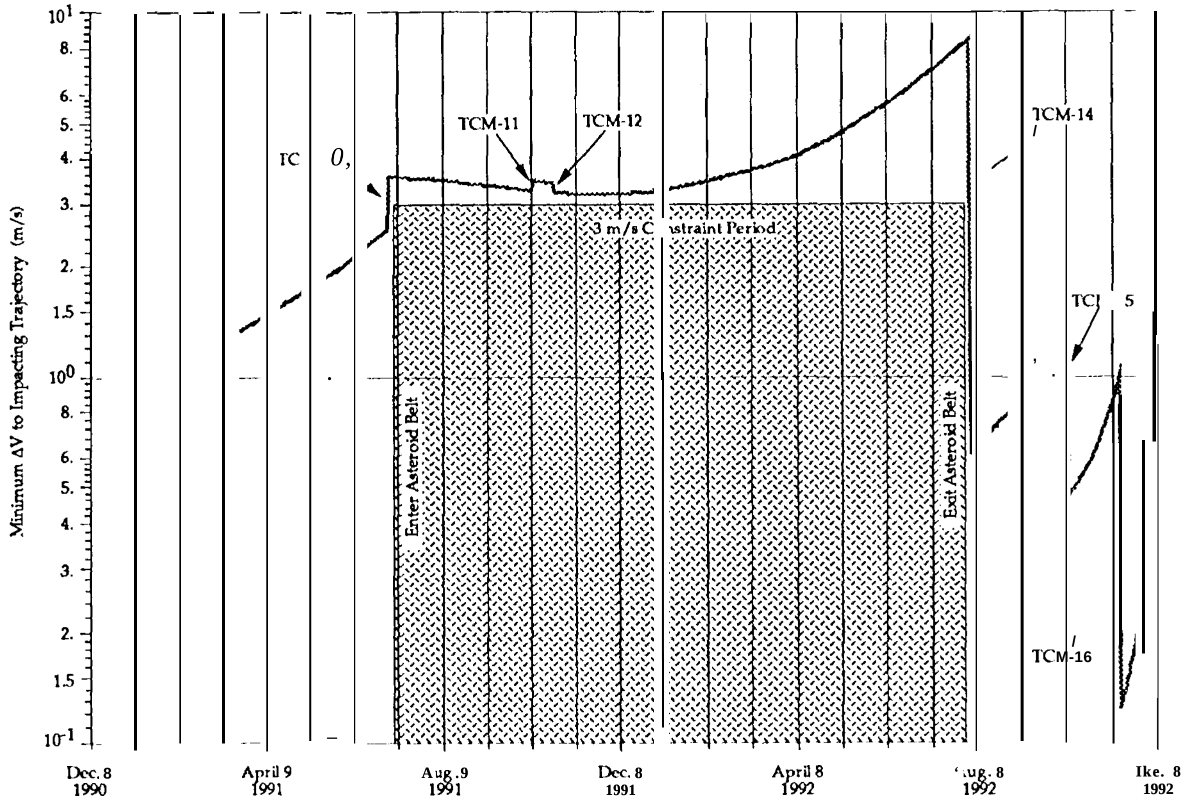
Due to the Earth navigation constraints, the design of TCM-9A included the design of representative maneuvers for TCM-9B and TCM-10 as well. These were representative designs in that statistical uncertainties and possible design assumption changes would affect the final design of these maneuvers. At the TCM-9A design epoch, TCM-9B was constrained to be a vector mode maneuver. This resulted in a purely lateral TCM-9B solution which was helpful in keeping the majority of the AV along a given thruster direction even in the presence of statistical errors. The Gaspra flyby aimpoint was constrained to be at a distance of 1600 km in b-plane magnitude and at 60" North ecliptic latitude. The target time for Gaspra closest approach was delayed approximately 25 minutes from the optimal solution. This was done at a small cost to provide ±20 minutes of dual deep space network station coverage around Gaspra closest approach. With this tracking coverage, a problem at a single station would not preclude receipt of engineering telemetry during the flyby. The delay included an extra 5 minutes to provide time of flight adjustment flexibility for the maneuvers which were to follow.

Orbit determination and TCM execution errors moved the TCM-9B inertial AV approximately 7" from the purely lateral direction, TCM-9B was designed assuming it would be the first unbalanced turn and burn maneuver. The design assured that a good star reference would be available for both TCM-9B and TCM-10, which was also planned to be performed in the same mode. Since TCM-9B was to be the first turn and burn maneuver, it was important that a simulation of the maneuver commands be performed on Galileo's testbed to increase performance confidence. Unfortunately, ground hardware problems with the testbed precluded the required simulation. Two weeks prior to the TCM execution, the maneuver reverted to vector mode which necessitated a i-Z axial segment at a cost of 0.5 kg of propellant.

On April 11, 1991 the high-gain antenna failed to unfurl completely during its scheduled deployment. A warming turn occurred on May 20, 1991 which was the first of many attempts to free the HGA. References [111 and [121 describe the details of the deployment anomaly and subsequent attempts to free the HGA. On May 30, 1991, the Galileo Project began replanning for the upcoming Gaspra encounter, relying upon the low-gain antenna (LGA) and the data management system (DMS, or tape recorder) to record the science data for later playback.

As a **consequence of the new plan to record Gaspra science data, the TCM-10** aimpoint **changed to a 1600 km dark side flyby at a 3.9" North ecliptic latitude. To provide a better background of stars for reference at the TCM-10 burn attitude, the turn was performed in a balanced mode and the closest approach time was adjusted 2 minutes earlier.** TCM-10 **was able to target to the** Gaspra aimpoint **and still satisfy the** 3 **m/s Earth navigation constraint (recall Figure 3) as a result of the prior planning at TCMS 9A and 9B. Figure 9 illustrates the minimum** ΔV to achieve an Earth impacting trajectory as a function of time, TCM-10 increased the minimum AV to impact to greater than 3 m/s prior to entering the asteroid belt. The trajectory satisfied the 3 m/s Earth navigation constraint by remaining outside the constraint region until exiting the asteroid belt.

Figure 9: Minimum ΔV to an Earth Impacting Trajectory



TCM-11 and TCM-12 were statistical maneuvers placed 20 and 5 days before Gaspra closest approach. They were necessary to meet the science delivery requirements for the Gaspra encounter sequence. The orbit determination solutions on the approach to Gaspra included

Galileo's first use of optical navigation data.[13] The optical data assisted in determining the position of the spacecraft relative to the target body. This relative position knowledge was crucial due to the apriori uncertainties in the Gaspra ephemeris. TheTCM-11 correction was based upon orbit determination data which included the first optical navigation image. Figure 9 shows that TCM-11 moved the trajectory further away from the 3 m/s Earth navigation constraint region.

Two entire maneuver designs were completed for TCM-12 (only one of which was uplinked). The second (or update) design was able to take advantage of the information in an additional optical navigation image received during the initial design. The nominal design began 13 days before TCM-12, while the fast update was initiated a week later. The update design was selected for uplink to provide the most accurate spacecraft delivery to the target aimpoint. A fourth and final optical navigation image was processed after TCM-12 execution to decide on the necessity of a pointing tweak for the science observations. Based on the predicted delivery error, the science pointing tweak was canceled, eliminating a time critical and potentially risky modification to the onboard sequence. The TCM-12 b-plane delivery error to Gaspra was 12 km and 15.5 seconds early based upon reconstruction estimates.

Gaspra to Earth 2

TCM-13 was scheduled 23 days after Gaspra to clean up post-encounter targeting dispersions. It also provided the opportunity to correct statistical errors in order to ensure satisfaction of the Earth navigation constraints. As Figure 9 demonstrates, TCM-12 reduced the minimum AV to impact slightly, but still satisfied the 3 m/s constraint. Since the Earth navigation constraints were met, TCM-13 was canceled at a cost of only 0.06 m/s.

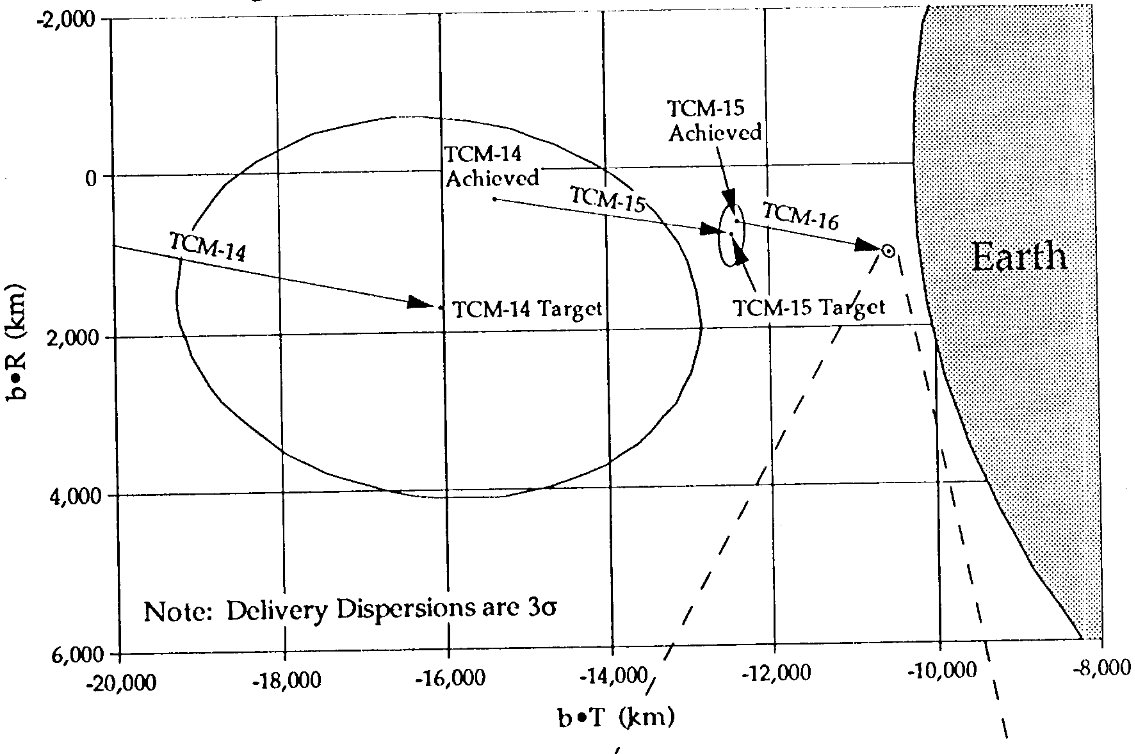
On August 4,1992 the 3 m/s constraint period ended, and the Galileo spacecraft immediately performed a large deep-space maneuver to move the trajectory as close to the Earth 2 aimpoint as the $1x10^{-6}$ probability of impact constraint would allow (see Figure 10). Instead of designing TCM-14 using the turn and burn sequence commands, the maneuver was separated into a single turn command followed by four days of vector mode commands for the burn. This strategy allowed the spacecraft to remain at the burn attitude between maneuver portions, which is more efficient than repetitive turn, burn, and turn back portions each day. Not only did it save propellant, but the execution strategy allowed a greater AV capability per day through a more effective use of the spacecraft memory allocated for the TCM. For science purposes, the Earth 2 time of closest approach was fixed, resulting in a small -Z axial AV component in addition to the 21 m/s lateral AV.

The geometry of TCM-14 provided data for a good reconstruction of the direction of the lateral AV. The navigation reconstruction estimated a 9.5 milliradian pointing error in the positive clock direction, which is equivalent to a 29 millisecond delay in the effective puke center of the lateral thrusters. For most maneuvers, this error source was not a major contributor to the TCM delivery accuracy. The current plan is to compensate for this directional AV bias within the ground software, This will be done in time for the next large lateral AV maneuver, TCM-22.

The next three TCMS, 15, 16, and 17, were similar in placement and strategy with their Earth 1 counterparts, TCMS 6, 7, and 8. One difference was that with the experience gained from the first Earth flyby, the Earth navigation strategy allowed for TCM-15 to target to a 2000 km minimum altitude limit up to 25 days before closest approach. Actual targeting for TCM-15 was to a 2017 km altitude.

Once again, 25 days before Earth, the trajectory was targeted to the optimal gravity-assist **aimpoint.** The targeted altitude for **TCM-16** was 304 km; approximate y three times closer than the first Earth flyby. The ideal **TCM-16 design** included a 0.008 m/s axial AV component, which represented a sub-sigma b-plane correction of 3 km and 2 seconds. The Galileo project policy is to avoid any unnecessary spacecraft activity, and the decision was made to delete this small axial AV segment. This decision resulted inTCM-16 being a purely lateral maneuver.

Figure 10: Earth 2 Target and Achieved Aimpoints



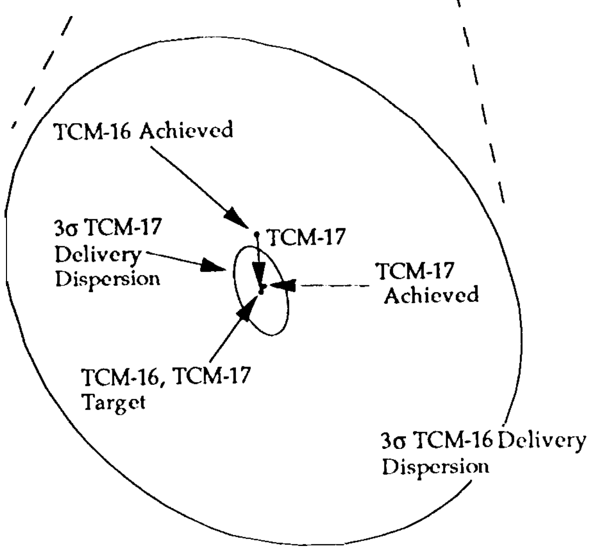


Figure 11: Earth 2 Mission Cost Contour

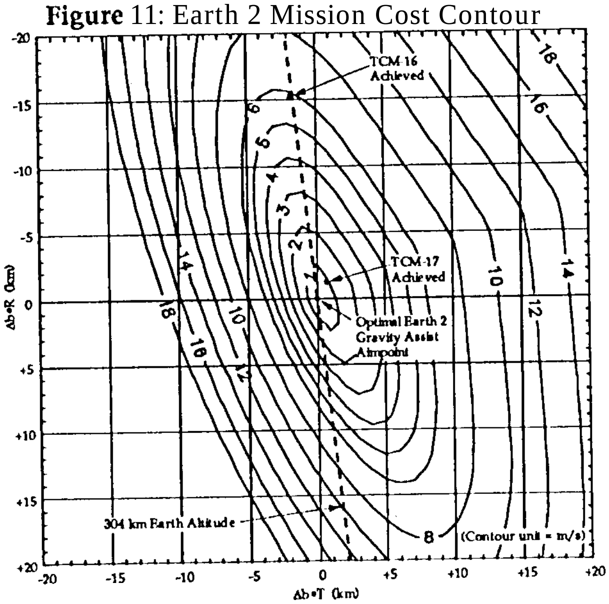


Figure 11 shows the achieved results from TCM-16 with respect to the Earth 2 cost contour. Future costs were estimated to be slightly less than 6 m/s if the trajectory was left uncorrected before the gravity assist. The asymmetry of the contour plot resulted from the vector mode constraint placed on the first post-Earth maneuver, TCM-18. Errors from the optimal aimpoint that were down and to the left in the b-plane caused the desired AV correction to be in the +Z direction at TCM-18. In practice, optimization of such an error resulted in a greater lateral AV at TCM-18 and a delay of part of the necessary correction to TCM-19. This would be done at a significant propellant penalty, but one that is an improvement over using the AV inefficient +Z thruster at TCM-18.

TCM-17 represented the final opportunity to clean up this delivery error prior to the Earth 2 gravity assist. TCM-17 was the smallest maneuver Galileo has performed at just .03 m/s to correct 15 km in the b-plane and 3 seconds in arrival time. Reconstruction solutions of the Earth 2 flyby estimate that the Galileo spacecraft came within 1.4 km in the b-plane and 0.1 seconds of the optimal gravity assist aimpoint. This precise flyby meant that only a 1 m/s statistical AV correction was necessary to compensate for the flyby error. The Earth 2 gravity assist had increased the spacecraft's heliocentric speed by another 3.7 km/s to a value of 39.0 km/s. The Galileo spacecraft now had sufficient energy to reach Jupiter,

Table 3 includes the target and achieved results for each flyby. The aimpoint miss is computed in the b-plane, b magnitude, altitude, and time of closest approach.

Table 3: Flyby Reconstruction

		b•R (km)	b•T (km)	b (km)	Altitude (km)	Date	Time (UTC) (hh:mm:ss.s)
Venus							
	Target	18,729.6	-22,814.8	29,518.0	16,125.6	10-Feb-1990	05:59:06.3
	Achieved	18,720.9	-22)18.7	29>15.5	16,123.2	10-Feb-1990	' 05:58:48.0
	A (aimpoint miss)	-8.7	-3.9	-2.5	-2.4		-00:00:18.3
	RSS Δb•R,Δb•T	9.5					
Earth 1							
	Target	-6,683,7	-9,051.4	11/251.7	952.0	08-Dec-1990	20:34:34.0
	Achieved	-6,690.5	-9,056.9	11,260.1	959.7	08-Dec-1990	20:34:34.4
	A (aimpoint miss)	-6.8	-5.5	8.4	7.7		00:00:00.4
	RSS Δb•R,Δb•T	8.7					
Gaspra							
	Target	-109.3	-1,596.2	1,599.9	1,592.9	29-Oct-1991	22:37:00.7
	Achieved	-97.9	-1/599.4	1,602.4	1/595.4	29-Ott-1991	223645.2
	A (aimpoint miss)	11.4	-3.2	2.5	2.5		-00:00:15.5
	RSS Δb•R,Δb•T	11.8					
Earth 2							
	Target	1,097.4	-10,530.0	10,587.0	303.8	08-Dec-1992	15:09:24.9
	Achieved	1,096.2	-10>29.2	10,586.1	303.0	08-Dec-1 992	15:09:24.9
	A (aimpoint miss)	-1.2	0.8	-0.9	-0.8		00:00:00.0
	RSS Δb•R,Δb•T	1.4					

Earth 2 to Ida

After the accurate Earth flyby, the first statistical maneuver, TCM-18, was not necessary. It was canceled at a cost of 0.4 m/s. It was also during this time that the science team requested a 40 minute later Ida closest approach time for better viewing geometry and to allow more science data recording at the encounter. This trajectory change would be done at TCM-19 at an additional cost of 0.7 m/s.

TCM-19 was used to correct the Ida target error which resulted from the Earth ftyby, and also to implement the closest approach time change for science purposes. With three target parameters (two b-plane and time of flight) and one maneuver to provide the correction, there is but a single inertial AV solution. TCM-19 was an ideal opportunity to perform the first turn and burn maneuver using unbalanced turns and referencing the gyros for attitude information during the maneuver. As mentioned previously, this will be the standard operating mode for maneuvers during the tour.

The eighteen previous maneuvers have successfully navigated Galileo through the VEEGA trajectory and placed the spacecraft on target for the upcoming asteroid encounter with Ida on August 28, 1993. Like the previous asteroid encounter, two statistical maneuvers prior to closest approach will utilize optical navigation data to achieve an accurate flyby trajectory. TCMS 20 and 21 are scheduled 15 and 2 days before Ida, respectively. The fast update for TCM-21 will be designed in only 3 days. The Galileo project continues to build and improve upon past experiences in an effort to maximize the science return.

PROPELLANT STATUS

Propellant usage predictions are based on Monte Carlo analyses of nominal trajectories. For a discussion of the methods of this kind of analysis refer to Reference [14]. Of primary importance to the process is an accurate prediction of orbit determination uncertainties at candidate maneuver epochs and an accurate understanding of all of the constraints influencing TCM design. Changes in these fundamental assumptions control the accuracy of the simulation process. The simulation process itself has changed significantly since launch with the development of linear simulation software for multi-maneuver optimization, based upon the work discussed in Reference [61. However, for the purposes of this paper, pre-launch analyses are still used as a measure for comparison.

A tabulation of predicted propellant usage vs. actual propellant consumption is given in Table 4. This information is provided to gauge the accuracy of predictions and to show how TCM propellant consumption has been minimized, The accuracy of the predictions are illustrated by comparing the predicted mean propellant usage with the actual in-flight values in terms of the predicted sigmas. Approximately 80% of the completed TCMS differ by 1 sigma or less from the predicted mean. Two of the multi-sigma differences were at TCM-4 (TCMS 4A and 4B) and TCM-14, which were large deterministic TCMS with small sigmas.

TCMS 4A and 4B were designed together to target to the first in a series of biased Earth 1 aimpoints. These two maneuvers were highly correlated and had a combined propellant uncertainty of approximately 0.4 kg. As such, the propellant actually used to implement TCM-4 changed significantly (-2.4 kg) from the pre-launch prediction. This change is due to a number of factors. TCM-4 benefited from an accurate Venus flyby and changes in the design of the trajectory. As a result of these factors, the required AV at TCM-4 differed from the pre-launch prediction by approximately -1 m/s and accounts for part of the difference. Propellant reductions are realized through both changes in the AV required and also by changes in the method of implementing the AV. As a result of the design strategy change discussed earlier, the implementation of TCMS 4A and 4B were able to use the lateral thrusters exclusively. Using the lateral thrusters with “benign” pulse widths allowed for more AV to be accomplished in a portion than was previously planned and thus shortened the maneuver durations at both TCMS 4A and 4B. TCM-4A and TCM-4B also benefited from the use of benign pulse widths because of a reduction in the burn arc losses associated with lateral thruster firings. A 3% reduction in propellant (-1.1 kg) was realized in TCM-4 through the use of the shorter pulse widths alone. All subsequent lateral maneuvers have also realized a 370 propellant savings as compared with the pre-launch predictions. A small contribution to the savings indicated in the table for TCM-4 is a result of the RPM reconstruction of the propellant expended, which shows a less than expected propellant loss due to the TCM (manifested as an underburn).

Table 4: Actual vs. Predicted TCM Propellant Consumption

Event	Execution Date	Location (Days)	Shift from Pre-Launch Location (days)	Predicted Bum Mass (kg) mean	sigma	90th	Actual Bum Mass (kg)	Actual vs prediction: Prediction (mean, kg)	Accuracy (n sigma)
Injection	19-Oct-89								
TCM-1 DSM	9-Nov-89	Inj.+21	1	18.8	5.0	25.9	16.52	-2.3	-0.5
TCM-2:M-2	22-Dec-89	Inj.+64	0	0.9	0.	1.5	1.14	0.2	0.5
TCM-3:M-3	29-Jan-90	V-12	Cancelled	0.3	0.	0.6	Cancelled		
Venus	10-Feb-90								
TCM-4A DSM	9-Apr-90	V+58	9	12.6	2.5	15.8	22.94	10.3	*
'KM-411 DSM	11-May-90	V+90	-10	23.3	2.3	26.4	10.53	-12.8	-5.8
TCM-5	17-Jul-90	E1-144	32	0.9	0.5	1.6	1.25	0.4	0.7
'KM-6	9-Ott-90	E1-60	0	0.8	0.2	1. 1	0.63	-0.2	-0.9
TCM-7	13-Nov-90	El-25	0	1.6	0.1	1,7	1.65	0.0	0.5
TCM-8	28-Nov-90	E1-10	0	0.1	0.1	0.2	0.10	0.0	0
Earth 1	8-Dec-90								
TCM-9A	19-Dec-90	E1+11	4	6.8	5.3	14.6	5.04	-1.8	-0.3
TCM-9B	20-Mar-91	E1+102	12	4.2	2.8	7.9	2.68	-1.5	-0.5
TCM10 DSM	2-Jul-91	G-119	-70	3.6	0.6	4.3	3.45	-0.2	-0.3
TCM-11	9-Oct-91	G-20	0	1.1	0.8	2.2	0.54	-0.6	-0.7
TCM-12	24-Oct-91	G-5	0	1.1	0.7	2.1	0.35	-0.8	-1.1
Gaspra	29-Oct-91								
TCM-13	21-Nov-91	G+23	Cancelled	3.5	2.5	7.0	Cancelled		
TCM-14 DSM	4-Aug-92	E2-126	0	21.8	0.3	22.2	19.86	-1.9	-6.5
TCM-15	9-Ott-92	E2-60	0	1.2	0.7	2.3	0.91	-0.3	-0.4
TCM-16	13-Nov-92	E2-25	0	2.0	0.1	2.1	0.82	-1.2	-11.8
TCM-17	28-Nov-92	E2-10	0	0.1	0.0	0.1	0.05	-0.1	-1.5
Earth 2	8-Dec-92								
TCM-18	21-Dec-92	E2+13	Cancelled	3.7	2.5	7.3	Cancelled		
TCM-19	9-Mar-93	E2+91	6	2.5	3.2	7.5	1.92	-0.6	-0.2
Summary				110.9	10.4	-	90.38	-20.5	-2.0

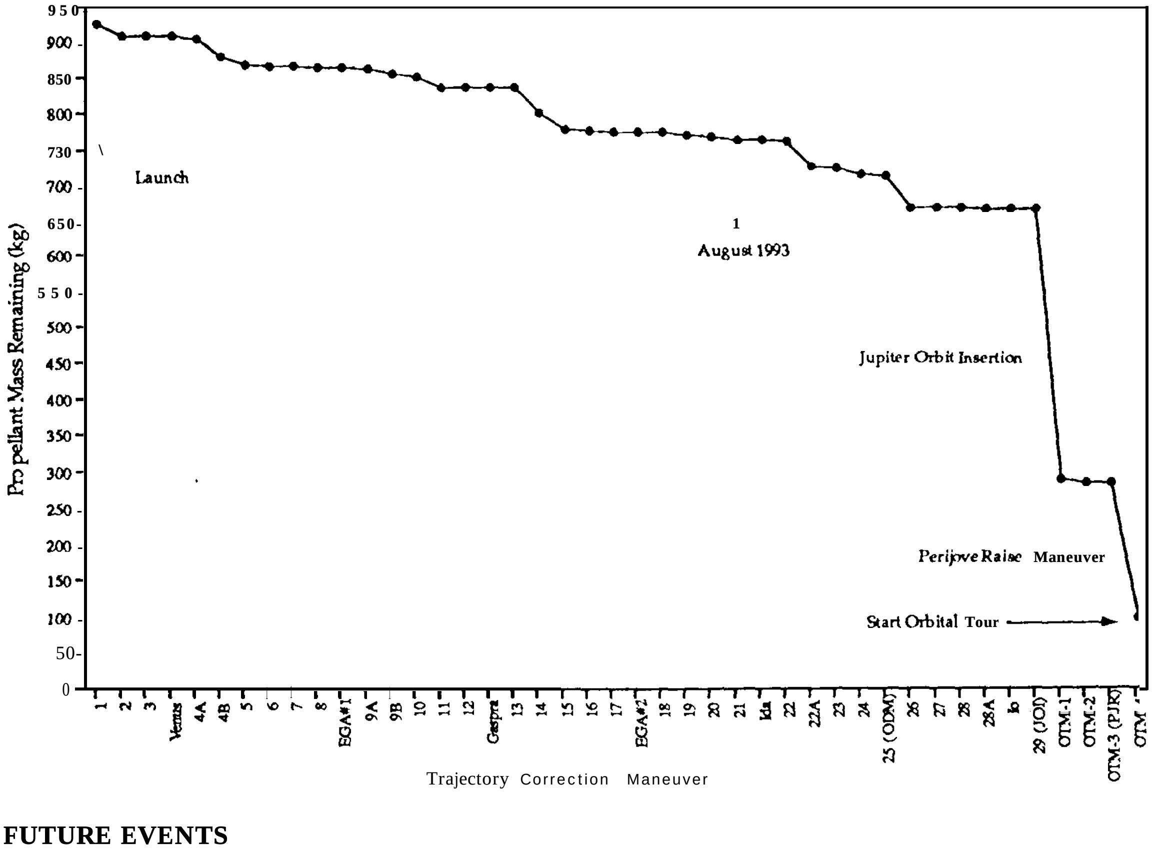
* TCM's 4A & 4B are strongly correlated. Combined sigma is .4 kg
Predicted ΔM 4A+4B = 35.9 kg. Actual ΔM = 33.5 kg. Δ = -2.4 kg.

Trajectory design changes sometimes allowed for a reduction in the required AV for maneuvers on approach to Earth 1. This did not imply an overall savings in the mission, because trajectory design changes (aimpoints changes at Earth and Gaspra) typically resulted in a reallocation of AV to downstream maneuvers. If AV can be delayed at little or no cost, it is sometimes wise to keep the propellant in the tank and let downstream statistical events influence the size of the delayed AV. Large statistical events, such as the errors introduced at an Earth flyby, can dominate downstream AV and reduce the "cost" of any delayed AV. The results on the Earth-Earth trajectory leg demonstrate this effect. Immediately following the Earth 1 flyby (TCM-9A design), the optimal trajectory to Gaspra and Jupiter, satisfying the constraints, resulted in a reallocation of AV amongst TCMS 9A, 9B, 10, 13 and 14 (small changes in other TCMS as well). At this point in the mission, all of the deterministic AV (5.6 m/see) that had been placed in TCM-13 was eliminated. (TCM-13 was eventual] y canceled, after the successful implementation of TCM-12.) The net effect of the Earth 1 flyby was a significant reduction in the required propellant on the Earth-Earth leg as is indicated in the table.

Not all of the propellant savings on the Earth-Earth leg were due to a successful Earth 1 flyby. TCMS 14, 15, and 16 implemented the Earth 2 approach strategy, satisfying the Earth navigation constraints. In the pre-launch analysis, the biasing strategy made no attempt to optimize the sequence of aimpoints stepping in to Earth 2. As a result, these vector mode maneuvers had a significant +Z component which was costly in terms of propellant. New aimpoints were selected after launch for each of the inbound maneuvers, resulting in mostly lateral AV for TCMS 14, 15, and 16 and a significant propellant savings. TCM-14 propellant reductions were also realized for many of the same reasons listed in the discussion of TCMS 4A and 4B. Benign pulse widths and trajectory design changes accounted for the majority of the propellant savings. An additional propellant savings (-.4 kg) in the implementation of TCM-14 resulted from a smaller spacecraft mass than was predicted for this point in the mission. In spite of significant propellant savings in navigating the spacecraft (which would impl y a larger spacecraft mass), these savings were more than offset by unforeseen non-navigation related propellant usage.

Since launch there have been significant changes affecting propellant usage and predictions. Attempts to free the high gain antenna have been unsuccessful to date and have used approximately 51 kg of propellant thus far. The satellite tour design activity has been completed and the nominal tour selected by the sci ence investigators. Planning is proceeding for the primary mission using the low gain antenna for data return. Figure 12 shows a history of propellant usage through August 1993, and predicted mean propellant usage up through the start of the tour. Note that by the start of the tour (post PJR) roughly 90% of the usable propellant will have been expended. Current predictions indicate a propellant margin of +5 kg, emphasizing the importance of continued propellant conservation efforts.

Figure 12 Propellant Mass



FUTURE EVENTS

Approximately one month after the Ida asteroid encounter on August 28,1993, TCM-22 will be the first maneuver to target directly to Jupiter. This 38 m/s AV will be the largest deep space maneuver for the Galileo spacecraft, and should be the largest AV performed using the 10

Newton thrusters during the entire mission. A critical event will occur 150 days before Jupiter, when the atmospheric probe is released on a ballistic trajectory targeted to specific entry conditions at Jupiter. The 400 Newton engine will then be accessible to deflect the orbiter to pass in front of 10. This will slow the spacecraft and reduce the AV required to enter orbit at Jupiter. Jupiter orbit insertion takes place on December 8, 1995, with a 645 m / s velocity change. Near apojove of the first orbit about Jupiter, a 375 m / s maneuver is designed to raise perijove from 4 to approximately 11 Jupiter planetary radii. The next twenty months will be full of activity as 31 orbit trim maneuvers arc scheduled to complete the Galileo tour.

CONCLUSIONS

The maneuver design process has accurately controlled the Galileo VEEGA trajectory through three planetary gravity assists and the first ever asteroid encounter. Trajectory and spacecraft operating constraints have been rigorously observed to successfully navigate the Earth flybys and protect the spacecraft instruments. Propellant conscious planning and improved optimization techniques have placed the Galileo spacecraft in excellent position to achieve the mission objectives at Jupiter.

ACKNOWLEDGMENT

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Hyperbolic approach trajectories arc typically described in aiming plane coordinates, often referred to as "b-plane" coordinates (see Figure A-1). The coordinate system is defined by three orthogonal unit vectors, $\underline{S}$, $\underline{T}$, and $\underline{R}$ with the system origin taken to be the center of the target body. Thes vector is parallel to the spacecraft hyperbolic approach velocity vector relative to the target body, while $\underline{T}$ is orthogonal to $\underline{S}$ and lies in the ecliptic plane (the mean plane of the Earth's orbit). Finally, $\underline{R}$ completes an orthogonal triad with $\underline{S}$ and $\underline{T}$.

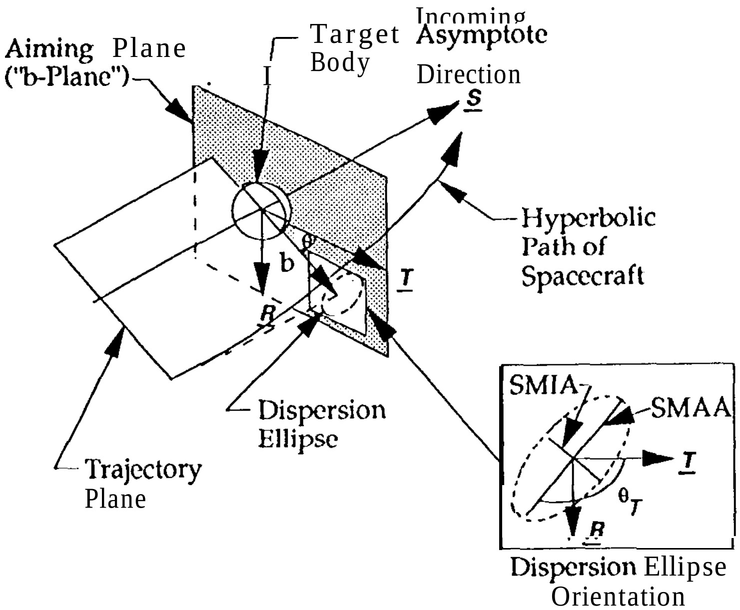

Figure A-1: Aiming Plane Coordinate System Definition

The aimpoint for an encounter is defined by the miss vector, ***b*** which lies in the $\underline{T}$-$\underline{R}$ plane, and specifies where the point of closest approach would be if the target body had no mass and did not deflect the flight path. The time from encounter (point of closest approach) is defined by the *linearized time-of-flight* (LTOF), which specifies what the time of flight to encounter would be if the magnitude of the miss vector were zero. Orbit determination errors are characterized by a one-sigma or three-sigma b-plane dispersion ellipse, also shown in Figure A-1, and the one-sigma or three-sigma uncertainty in LTOF. In Figure A-1, SMIA and SMAA denote the semi-minor and semi-major axes of the dispersion ellipse, respectively.